Crab Cavity RF Noise Studies

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May 8^{th} 2014

Introduction

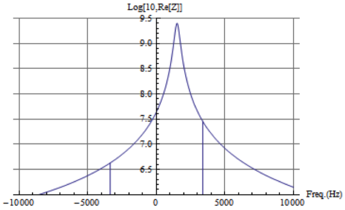
The LLRF architecture has a significant impact on:

- Coupled-bunch instabilities
  - Presented in detail on Tuesday (P. Baudrenghien)
- Power Considerations
  - Main cavity phase modulation and consequences
- RF Noise
  - Emittance growth due to Amplitude/Phase noise
  - Luminosity reduction due to Phase noise

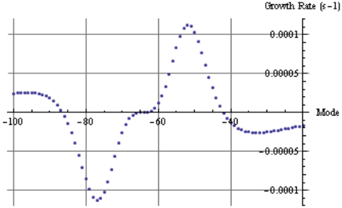
Trade-offs exist between these topics and have been investigated

Stability Summary from Tuesday (P. Baudrenghien)

- With the RF FB Off, the cavity will be detuned away from the betatron sidebands ($\approx$ 1.5 kHz)
  - Cavity on-tune is ideal for stability, but cavity detuning in the wrong direction would lead to being problems
  - The resulting fastest growth rates (1 s^{-1}) are almost three order of magnitude slower than the damping time of the transverse damper ($\approx$1 ms)
- With the RF FB On, the fastest growth rates are an *additional* three orders of magnitude lower
  - Sensitive to LLRF settings, but margin of stability really big
  - Freedom to manipulate RF FB as needed for other considerations



Cavity Impedance with RF FB Off.



Growth rates with RF FB On.

Emittance growth due to RF noise

- Emittance growth due to the crab cavity noise is the most concerning issue
- An expression has been derived relating the crab cavity noise power spectral density with the emittance growth rate

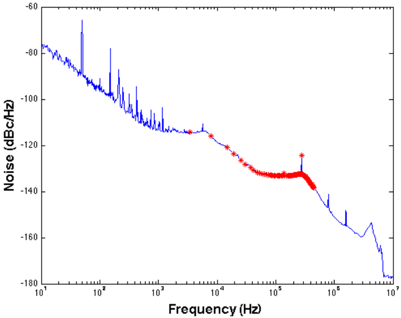
$$\begin{aligned}\frac{d\epsilon_x}{dt} &= N\Big[\frac{\beta_{cc}}{2}\Big(\frac{eV_{cc}\sigma_\phi f_{rev}}{2E_b}\Big)^2 \sum_{m=-\infty}^{\infty} S_{\Delta A}(f \pm f_b \pm f_s - mf_{rev}) + \\ &+ \beta_{cc}\Big(\frac{eV_{cc} f_{rev}}{2E_b}\Big)^2 \sum_{m=-\infty}^{\infty} S_{\Delta\phi}(f \pm f_b - mf_{rev})\Big]\end{aligned}$$

- On the LLRF side, the goal is to reduce the noise power spectral density at the betatron sidebands
- It is possible to determine the expected growth rate with an estimate of the crab cavity noise power spectral density
- Let's focus on the phase noise contribution for the next couple of slides

Emittance growth due to phase noise

Estimation with LHC main cavity measurements

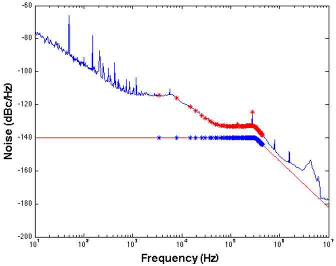
- First, we estimate the expected emittance growth rate using the measured power spectral density of the LHC main cavities (figure)
- The transverse emittance would increase by 60% over an hour with this power spectral density! ($V_c = 3.4$ MV, $\epsilon_n = 3.75$ microns, $\beta_{cc} = 3500$ m)
  - Including the ≈30 reduction through the action of the transverse damper
- So, what do we do? Clever RF FB techniques are required



Emittance growth due to phase noise

Contributions and expected reduction

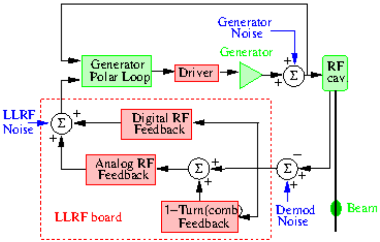
- The 1/f noise from the crystal oscillator is not an issue (first sideband at $\approx$ 3 kHz)
- The noise up to $\approx$ 20 kHz is from the transmitter. Tetrodes are less noisy than klystrons, so we anticipate a much lower noise level
- The contributions up to the closed loop cavity bandwidth of $\approx$ 300 kHz are dominated by the analog demodulator in the RF FB.
    - For an emittance growth rate of approximately 5%/hour the demodulator noise level should be in the order of -140 dBc/Hz (very challenging)

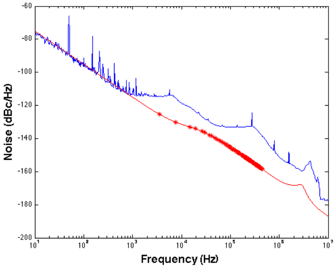


Emittance growth due to phase noise

Bandwidth reduction

- A more realistic scenario would involve a significant reduction of the RF FB bandwidth with a corresponding increase in the generator polar loop bandwidth
  - Effectively this is a careful optimization of the LLRF loop parameters based on the specific noise sources
  - But, we have experience in developing appropriate models and tools to achieve this
  - Generator polar loop gain increased by 17 dB, RF FB gain reduced by 10 dB
  - With the modeled power spectral density below, it should be possible to achieve a 5% transverse emittance growth rate

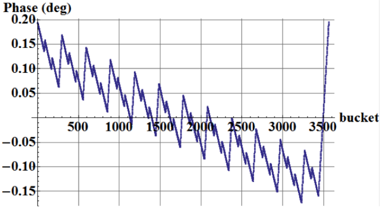




Emittance growth due to phase noise

Bandwidth reduction: Cons

- The reduced RF FB bandwidth will limit the beam loading compensation
- Only an additional $\pm 0.2^\circ$ error though due to high cavity Q_L



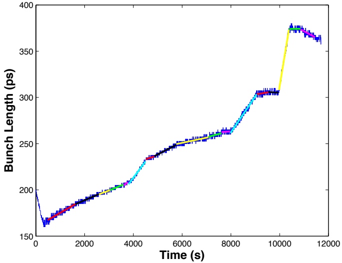
Transverse damper

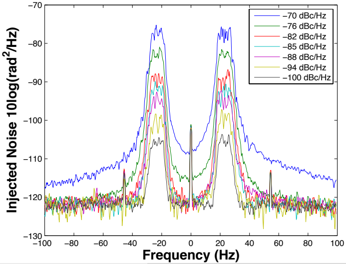
- Increasing the transverse damper gain at low frequencies could also help a little, with negligible effects on damper stability and injection of BPM noise through the damper

In the end, a combination of LLRF parameter optimization and component improvement will be necessary. Measurements will be necessary.

SPS Tests

- SPS tests will help validate our models and decide on the optimal strategy
  - Emittance growth in the SPS is dominated by other factors
  - We faced a similar issue in the case of longitudinal emittance growth due to the main LHC RF system (growth dominated by IBS)
  - Solution: artificially injected noise until we saw a result in the emittance growth rate
- Measurement with the *actual* components will be necessary to determine the best configuration of the LLRF tool
  - Polar loop will be installed in the tetrode test stand by the end of the year, so we will have more accurate information soon
  - Renovated SPS damper will allow detailed studies on the effect of the damper





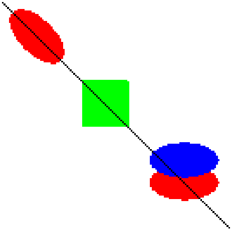
Emittance growth due to amplitude noise

- Since the phase noise is dominated by the analog demodulator, the amplitude noise is closely related to the phase noise: $\Delta A = \frac{\Delta V}{V} = \Delta\phi$
  - This assumption holds for the main RF. Measurements will be conducted on the SPS test stand to verify
  - Amplitude noise is about a factor of 50 lower. The transverse damper though cannot act on amplitude noise (head-tail motion rather than bunch motion), so in the end the phase and amplitude noise contributions are comparable $\rightarrow$ total emittance growth rate is about 60% higher

Luminosity reduction due to RF noise

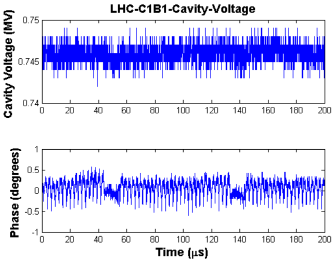
- The phase noise jitter also translates to a jitter in the IP transverse position
- For emittance growth purposes, we aim to 40 μrad rms phase noise per cavity
- Corresponds to at most a 3 nm transverse position jitter for a 6 μm beam size $\rightarrow$ no issues anticipated

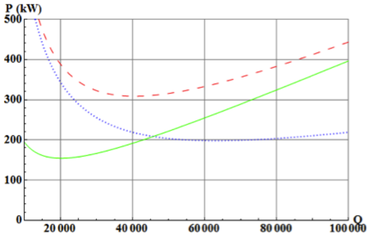
$$\Delta x = \frac{c\theta_c}{\omega_{RF}} \Delta\phi$$



Main cavity phase modulation: background

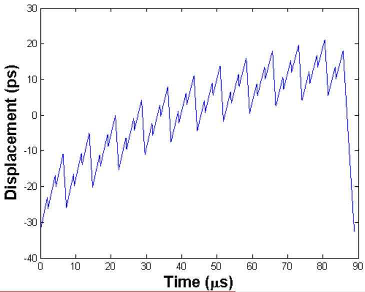
- RF/LLRF currently setup for extremely stable RF voltage (minimize transient beam loading effects). Less than 1° RF phase modulation (7 ps)
- To continue this way, we would need at least 200 kW of klystron forward power at nominal beam current (0.58 A DC)
    - Klystrons saturate at 200 kW with present DC parameters (ultimately 300 kW). Sufficient margin necessary for reliable operation, additional RF manipulations etc.
    - The present scheme cannot be extended beyond nominal. Graphs for nominal (1.15e11 ppb, 25 ns, 7 TeV, 0.58 A DC), ultimate at 450 GeV (1.7e11 ppb, 25 ns, 0.86 A DC), ultimate at 7 TeV

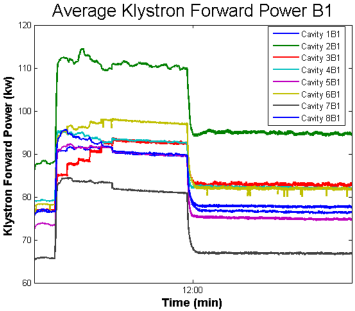




Main cavity phase modulation: solution

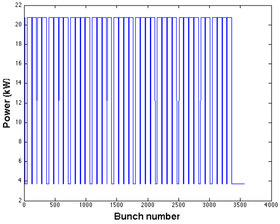
- For beam currents above nominal (and possibly earlier), we will accept the cavity phase modulation by the beam in physics (transient beam loading), but keep the strong RF/OTFB for loop and beam stability
- To achieve this, we have to adapt the voltage set point for each bunch
- An iterative algorithm has been developed, which is independent of beam current, cavity voltage and Q_L
- Significant reduction of klystron forward power expected
- Existing RF would be sufficient even for High-Lumi LHC (1.1 A DC)

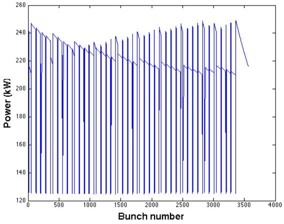




Main cavity phase modulation: consequences

- If the crab cavity follows the phase modulation
  - Power requirements increase significantly: up to 170 kW with optimal Q_L (44,000), 950 kW with Q_L = 500,000!
  - Transmitter more expensive. More importantly, windows too small for all this power
- If the crab cavity phase is fixed:
  - No power requirement change
  - There will be an error between the cavity and beam phase, leading to a transverse displacement at the IP
  - This displacement is comparable to the transverse beam size
  - BUT, it is common for both beams, so there is no loss of luminosity, only a modulation of the vertex's transverse position (acceptable to the experiments)





Conclusions

- The impedance at the fundamental is not a problem, thanks to the RF feedback
- The main RF cavity phase modulation algorithm would lead to an IP transverse position modulation, comparable in size to the beam
- We have formulas for the transverse emittance growth caused by RF noise
  - Early estimates are a bit alarming
  - Clever RF FB techniques will be necessary to achieve a 5% transverse emittance growth rate
  - Detailed studies on the way
- No direct luminosity reduction expected due to the RF noise

Thank you for your attention